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PRELIMINARY VERIFICATION OF THEORY

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ABSTRACT

Experimental results are presented which tend to validate a previously developed theory of sound production in the human lung over a particular Reynolds number range. In addition, a new, presently nonunderstood, phenomenon was observed at higher Reynolds number. These results, which show how sound generation in the lung depends upon the physiologically important variables of volume flow rate and bronchial diameter, have potentially important application in noninvasive lung examination and the diagnosis of lung disease.

INTRODUCTION

In a recent paper[1], Hardin and Patterson developed a theory of sound generation in the human lung based upon the observation by Schroter and Sudlow[2] that low Reynolds number flow in a repeatedly branching system such as the bronchial tree produces vortices in each branch. Two and four vortices are generated in each of the bronchial tubes in the correct Reynolds number range by inspiratory and expiratory flows respectively. Hardin and Patterson analyzed a mathematical model of this phenomenon which consisted of rectilinear vortex filaments in a rigid cylinder and found that the vortex cores execute orbits

whose size is dependent upon the position of formation of the vortices. This oscillation, which has been observed during flow visualization by the present authors, is responsible for the production of sound which can be calculated from the Coriolis acceleration of the vortices utilizing the vortex sound theory of Powell[3].

When this analysis is coupled with a model of the human bronchial tree, such as that of Weibel[4], relations between the frequency of sound generated in each order of bronchi and the physiologically important variables of volume flow and bronchial diameter are obtained. This result is of immense potential significance as it may allow the development of a noninvasive technique for lung diagnosis. The amplitudes and frequencies of the sound generated at moderate flow rates are high enough to be readily discerned and appear to change dramatically with small perturbations of the internal lung geometry[1]. Thus, after a period of human testing to determine the sound signature of various lung diseases and the natural variability from person to person, the early diagnosis of potential lung problems should be possible.

The purpose of this paper is to present preliminary experimental evidence which tends to verify the theory of Hardin and Patterson[1] over a particular Reynolds number range as well as to suggest the presence of another, as yet not understood, phenomenon at higher Reynolds number which may also be useful in the diagnosis of lung disease.

EXPERIMENTAL APPARATUS AND DATA ANALYSIS

The basic building block of the bronchial tree is a Y-tube where the flow from two branches is merged into one or the flow from one branch is split into two, dependent upon whether expiratory or inspiratory flow is considered. The

vortices observed by Schroter and Sudlow[2] are produced by the necessity of changing the direction of flow through an angle at the branch. Since this is the simplest configuration for which the theory is valid, it was decided that the preliminary acoustic testing should be carried out on a single Y-tube. A full size sketch of the model is shown in figure 1. It is made of glass and is nominally symmetric. The diameters and branching angle of the tube were chosen to approximately represent the 4th and 5th orders of bronchi in the human lung[4]. For the purpose of discussion, the standard description of the larger branch as the "parent" and the smaller branches as "daughter" will be employed. The lengths of the branches are considerably longer than those in the lung, which are typically 3 diameters, for ease of manufacture and testing. The theory indicates that the tube lengths are not critical to the sound generation process.

For testing, the tube was placed in a large (approximately 2.5 x 3.4 x 4.0 meters) anechoic chamber with a low frequency cut-off of 150 Hz. Figure 2 is a photograph of the model in position for testing. The anechoic chamber was primarily used to reduce the influence of external ambient acoustic disturbances which would otherwise mask the desired acoustic phenomena. Tests were made only in the expiratory mode due to the additional complication of two matched sound sources present for the inspiratory case. As can be seen in figure 2, a 2.54 cm microphone (frequency response flat over 10-15,000 Hz) with its cap removed was placed at 90° to the axis of the parent tube as close as possible (≃1 cm) to the tube without flow impinging on the microphone itself.

Flow was supplied to the model by a system which is shown schematically in figure 3. The standard shop air supply (pressure 6×10^5 Newton/m^2) was passed through a series of two control valves in order to reduce it to the

small pressures and flow rates required for this testing. The flow then went into a flow meter to measure the volume flow which then gave the test velocity through knowledge of the tube area. Finally, the flow exited into an acoustic muffler to remove noise generated in the flow reduction sequence. The muffler actually was a commercial water filter housing in which a dual chamber filled with fiberglass produced very low background noise levels at all flow rates of interest in the tests, as will be seen in subsequent spectra.

The flow then passed through a very long supply tube (≈7 m) into the anechoic chamber and was split by a commercial Y-tube into the two flows required by the test. The commercial Y-tube had all three branches of the same diameter, 0.954 cm, and thus the flow was decelerated upon passing through this junction. Each flow then proceeded through a contraction section to reduce it to the diameter, 0.34 cm, of the daughter branches of the model and then through Tygon tubes of approximately 0.5 m in length before entering the model. Noise spectra which were obtained at each juncture of this flow system were broadband with no unusual features.

Tests run over the Reynolds number ($R_e = U_o D_o/\nu$ where U_o and D_o are the velocity and diameter of the parent tube, respectively, and ν is the kinematic viscosity of air) range 50-4500 where Schroter and Sudlow[2] observed the vortices were completed. Below the Reynolds number of 965, nothing could be observed over the background noise of the system. Of course, this range corresponds to very low pressures and flow rates in the system. As the flow rate was further increased, intense tones began appearing in the spectrum. These tones formed a harmonic series with the amplitude of the fundamental at least 20 dB above the background level and 15 dB above the level of any harmonic, of which there were

as many as nine readily observed. A typical spectrum in this region is shown in figure 4. This behavior was observed up to Reynolds number of 1488 where the tones completely disappeared into the background level. Over this range, the fundamental frequency varied from 200 to 360 Hertz.

When the flow rate was still further increased, nothing interesting was observed until the Reynolds number of 1787 was reached where a new set of tones appeared. These tones were much higher in frequency and again formed a harmonic series with the fundamental amplitude 30 dB above the background level and 10 dB above the highest harmonic amplitude. As many as four harmonics were seen in the range of analysis. A typical spectrum in this region is shown in figure 5. This behavior was observed up to the Reynolds number of 2360 where the tones again disappeared into the broadband flow noise. Over this Reynolds number range, the frequency of the fundamental varied from 1210 to 1775 Hertz. Further increases in flow rate showed no further interesting behavior, only a general rise in the broadband flow noise. These phenomena were quite repeatable, appearing at the same velocities regardless of whether the flow rate was being raised or lowered and turned on and off quite sharply with only small changes in velocity.

This experiment was designed to test the theory developed by Hardin and Patterson[1] for sound production in the human lung. This theory predicted that, on expiration, each bronchus with flow in the Reynolds number range 50-4500 would generate sound with fundamental frequency, f_o, given by

$$f_o = 0.212 \frac{U_o}{D_o} \left(\frac{D_o}{D_1} \right)^2 \tag{1}$$

where U_o and D_o are the previously defined velocity and diameter of the parent

bronchus respectively and D_1 is the diameter of the daughter bronchi (assuming symmetry). The theory also predicts that the first harmonic of this frequency will be generated as well. Note that the theory shows the frequency to be directly proportional to the velocity, i.e. as the velocity goes to zero, the frequency goes to zero.

In figure 6, this theory is compared with the data obtained in this experiment. The figure is a plot of the frequencies at which the tones appeared as a function of the Reynolds number of the flow in the parent tube. The tone frequencies were obtained directly from the acoustic spectra such as figures 4 and 5, and the Reynolds numbers were calculated from the known velocity and diameter of the parent tube using the value of 0.154 cm^2/sec for the kinematic viscosity of air. Note the appearance of several harmonics as discussed earlier.

For the purpose of this comparison, Eq. (1) has been rewritten in terms of the Reynolds number as

$$f_o = 0.212 \frac{\nu}{D_1^2} R_e \tag{2}$$

This linear relation is the solid line marked "Theory" on figure 6. As can be seen, this theory agrees quite well with the fundamental frequency of the phenomenon observed in the lower Reynolds number range, $965 \leq R_e \leq 1488$. The tone frequencies exhibit a linear dependence upon Reynolds number whose slope is almost precisely that predicted by the theory, although the theory does slightly overpredict the frequencies themselves. This slight overprediction is probably due to the upper bound estimate of the circulation of the vortices employed in reference 1.

The phenomenon observed in the higher Reynolds number range, $1787 \leq Re \leq 2360$, however, appears to be something different. Although the frequencies are still a linear function of the Reynolds number, the slope is much greater than

that found in the lower Reynolds number range. Further, if the phenomenon were extrapolated back to lower Reynolds numbers, it is clear from the figure that the frequency would go to zero at a finite Reynolds number rather than zero as the other phenomenon did. Thus, it seems clear that the flow physics which produce these two phenomena are different. The beauty of the second phenomenon, in terms of lung diagnosis, is that its higher frequencies are more easily discerned above the background levels in typical examination environments. Further testing should allow it to be understood and predicted just as is the first phenomenon.

DISCUSSION OF RESULTS

In their initial visualization studies of flow in Y-tubes, Schroter and Sudlow[2] claimed to have observed four vortices in expiratory flow over the entire Reynolds number range $50 < Re < 4500$. This is supported by the work of Hardin, Yu, Patterson and Trible[5] who found the pressure/flow relation in a larger four order model of the bronchial tree not to vary over this range. The present study, however, suggests that at least two different phenomena occur in this same Reynolds number range.

One possible explanation for these differing results is that a critical variable is not being controlled in the experiments. It is the present authors' suspicion that this variable is the geometry of the junction. Schroter and Sudlow[2], who used "perspex" tubes, made an initial study of this effect. They utilized two tubes having the ratio of the radius of curvature of the outer wall of the junction to the radius of the parent tube equal to one and four respectively and found that a large region of reversed flow occurred in the first model while the flow in the second remained attached. However, the effect of the carina or flow divider where the two daughter tubes meet was not considered.

In the present study, where glass tubes were employed, the experimenters had very little control over the geometry of the junction, having to take whatever the glass shop produced. This often resulted in quite wavy walls in the region of the junction. Thus, some tubes were tested in which no tonal phenomena were observed. Others were tested in which the tone phenomena were not as distinct as those reported here. Such assymmetries would also explain the appearance of many harmonics in the data, while the theory predicted only one.

In attempting to study a laminar flow phenomenon, particularly in the region above Re = 2000 where Poiseuille flow in the tube would tend to go turbulent[6], it is not surprising that inflow and geometric conditions should be critical to the experiment. Thus, the present authors have planned a further series of tests which will employ machined tubes and rubber lined tubes to control the geometry and to yield more precise inflow conditions. These considerations are not important in the actual human lung as physiological surfaces tend to be smooth such that the inflow is laminar.

Another phenomenon which was observed in earlier tests with larger tubes was the presence of organ pipe tones. These are readily recognized as they tend to form an almost harmonic series with fundamental frequency given approximately by[7]

$$f_o = \frac{c}{4L} \tag{3}$$

where c is the speed of sound and L is the length of the tube. Thus, the frequency of this series of tones does not change as the flow in the tube is changed.

Finally, it is of interest to comment on the fact that at least two different phenomena were observed. This behavior is reminiscent of that

produced by flow over a cylinder[8]. At low Reynolds number, the wake consists of a very orderly vortex street. As the flow speed is raised, the wake degenerates into a very confused motion in which no order can be observed. Then, with a still further increase in speed, the orderly vortex street returns once more until, at a very high Reynolds number, it disappears and returns no more.

What may be happening in the Y-tube is that the flow is initially in the stable four vortex configuration observed by Schroter and Sudlow[2]. Then, as the flow is increased, this configuration becomes unstable and confused. A further increase may then find the flow in a new stable configuration, such as eight vortices, which then degenerates into turbulence. Such state transitions are quite commonly observed in laminar flows[9], although precise prediction of such behavior has not yet been achieved. More extensive visualization and measurement programs are planned to better understand this behavior.

CONCLUSION

This paper has presented experimental results which tend to validate a previously developed theory of sound generation in the human lung over a particular Reynolds number range. In addition, the presence of a second phenomenon is reported. These phenomena have important application in the diagnosis and prevention of lung disease as they allow the determination of bronchial diameters from spectra of sound produced by the lung. Further experiments are needed to increase the understanding of this second phenomenon and to better define the critical parameters of the lung sound generation process.

REFERENCES

1. Hardin, J. C. and Patterson, J. L., Jr.: Monitoring the State of the Human Airways by Analysis of Respiratory Sound. Acta Astronautica, vol. 6, 1979, pp. 1137-1151.

2. Schroter, R. C. and Sudlow, M. F.: Flow Patterns in Models of the Human Bronchial Airways. Resp. Physiol., vol. 7, 1969, pp. 341-355.

3. Powell, A.: Theory of Vortex Sound. J. Acoust. Soc. Am., vol. 36, 1964, pp. 177-195.

4. Weibel, E. R.: Morphometry of the Human Lung. Academic Press Inc., New York, N.Y., 1963.

5. Hardin, J. C.; Yu, J. C.; Patterson, J. L., Jr.; and Trible, W.: The Pressure/Flow Relation in Bronchial Airways on Expiration. Biofluid Mechanics 2, Ed. by D. Schneck, Plenum Press, New York, 1980.

6. Prandtl, L. and Tietgens, O. G.: Applied Hydro- and Aeromechanics, Chap. II, Dover Publications, New York, 1934.

7. Rayleigh, C. W. S.: Theory of Sound. Vol. II, Chap. 12, Dover Publications, New York, 1945.

8. Roshko, A.: Experiments on the Flow Past a Circular Cylinder at Very High Reynolds Numbers. J. Fluid Mech., vol. 10, pt. 3, May 1961, pp. 345-356.

9. Monin, A. S. and Yaglom, A. M.: Statistical Fluid Mechanics. Vol. 1, Chap. 2, M.I.T. Press, 1971.

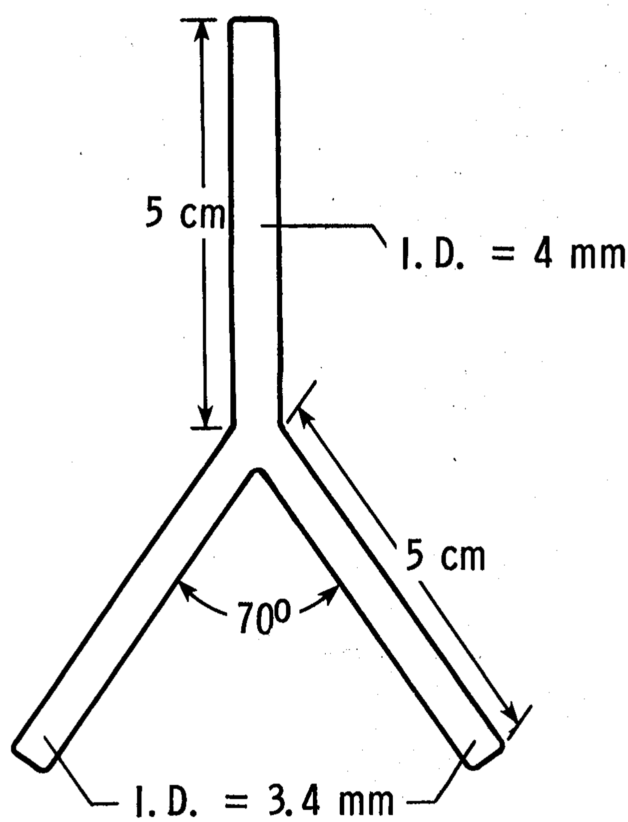

Figure 1: Full Scale Sketch of Experimental Model

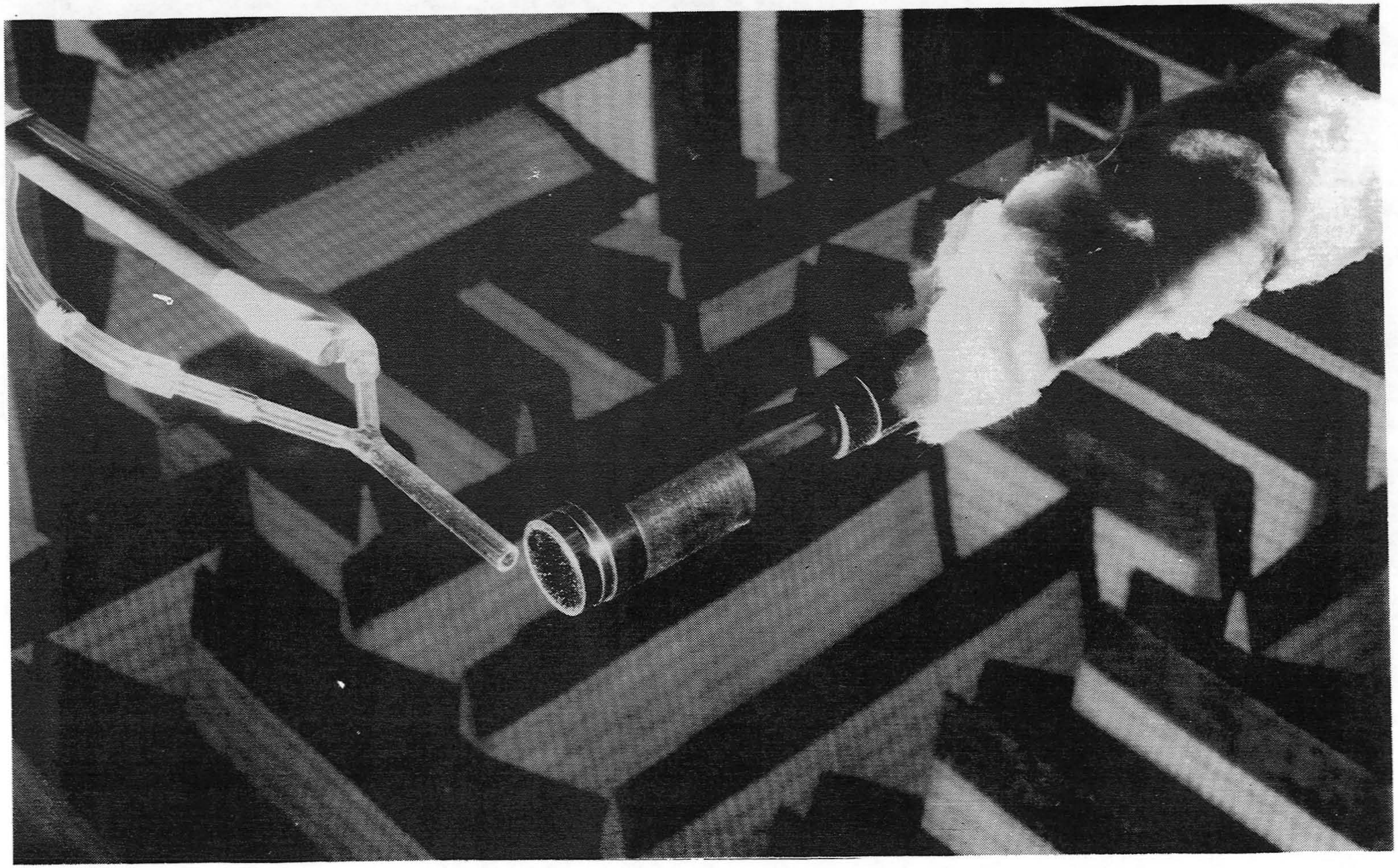

Figure 2: Model in Anechoic Chamber

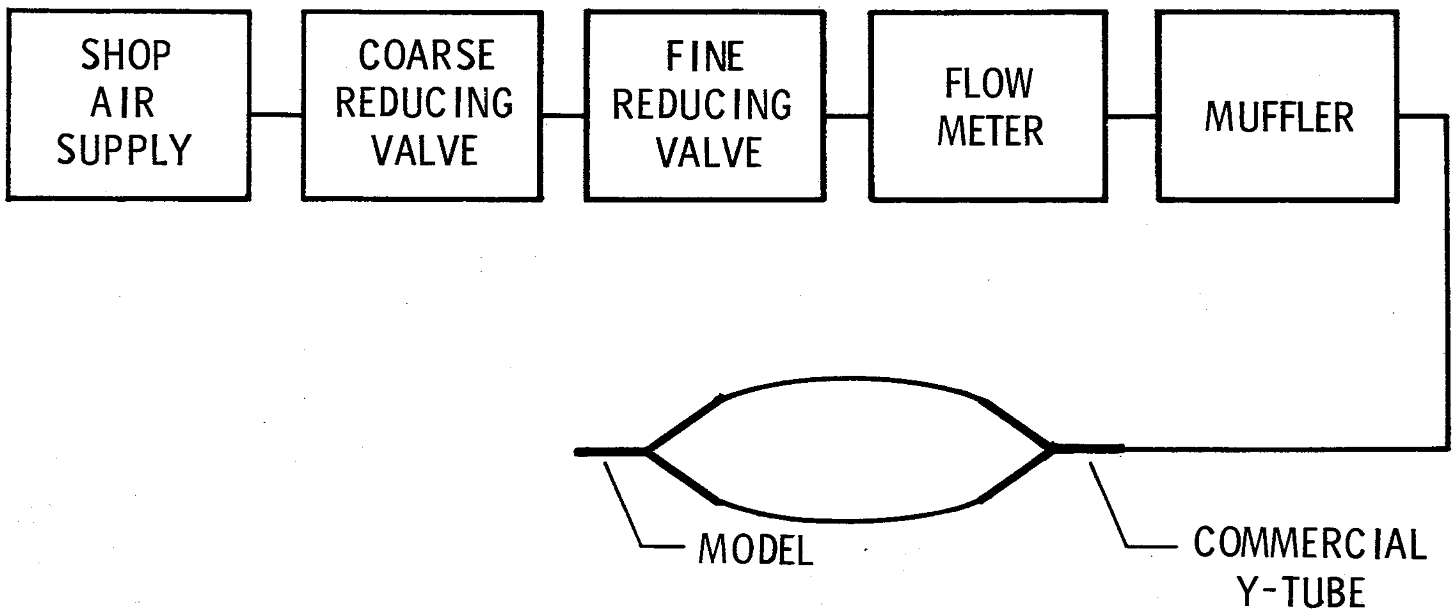

Figure 3: Schematic of Flow Supply

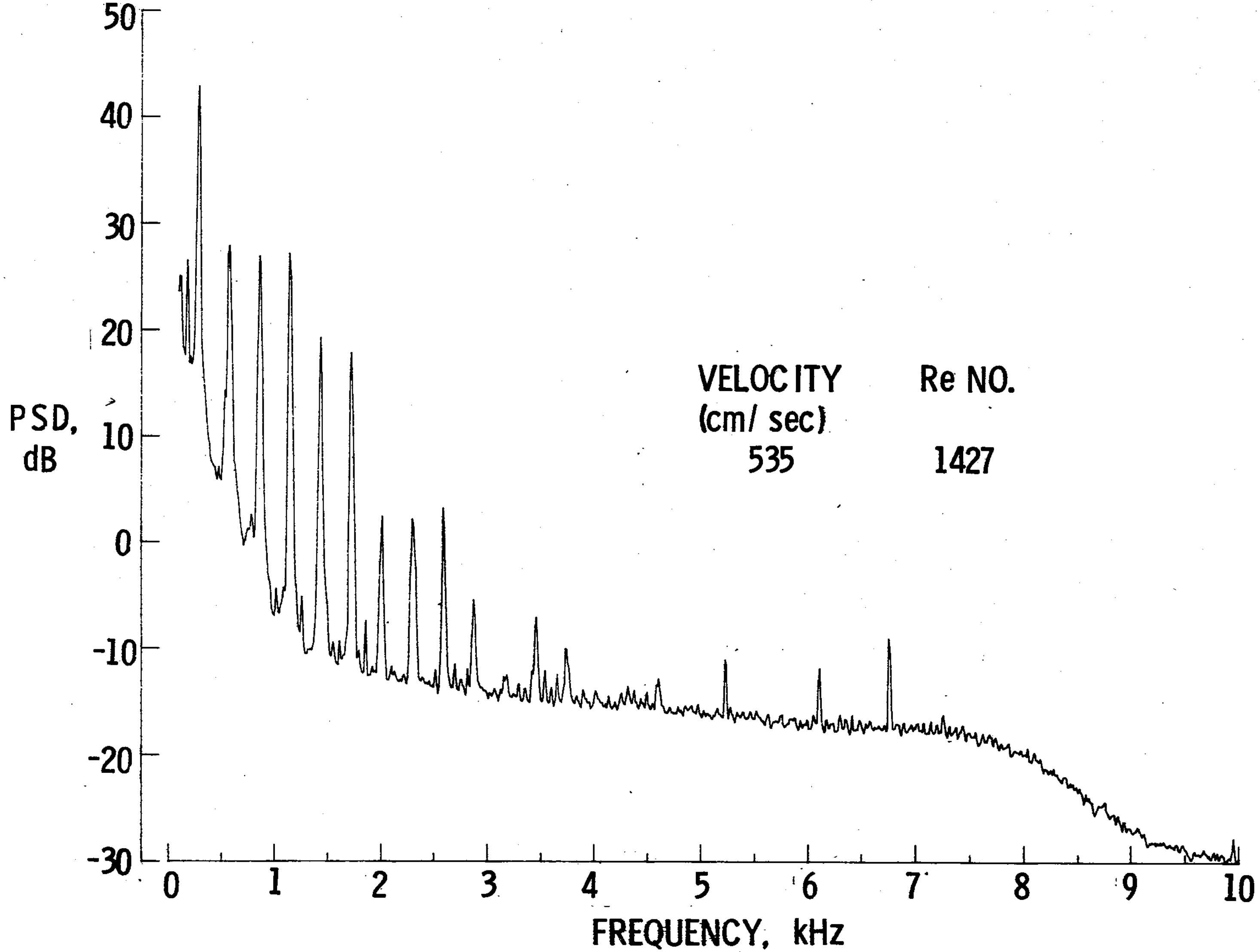

Figure 4: Typical Spectrum in Lower Region

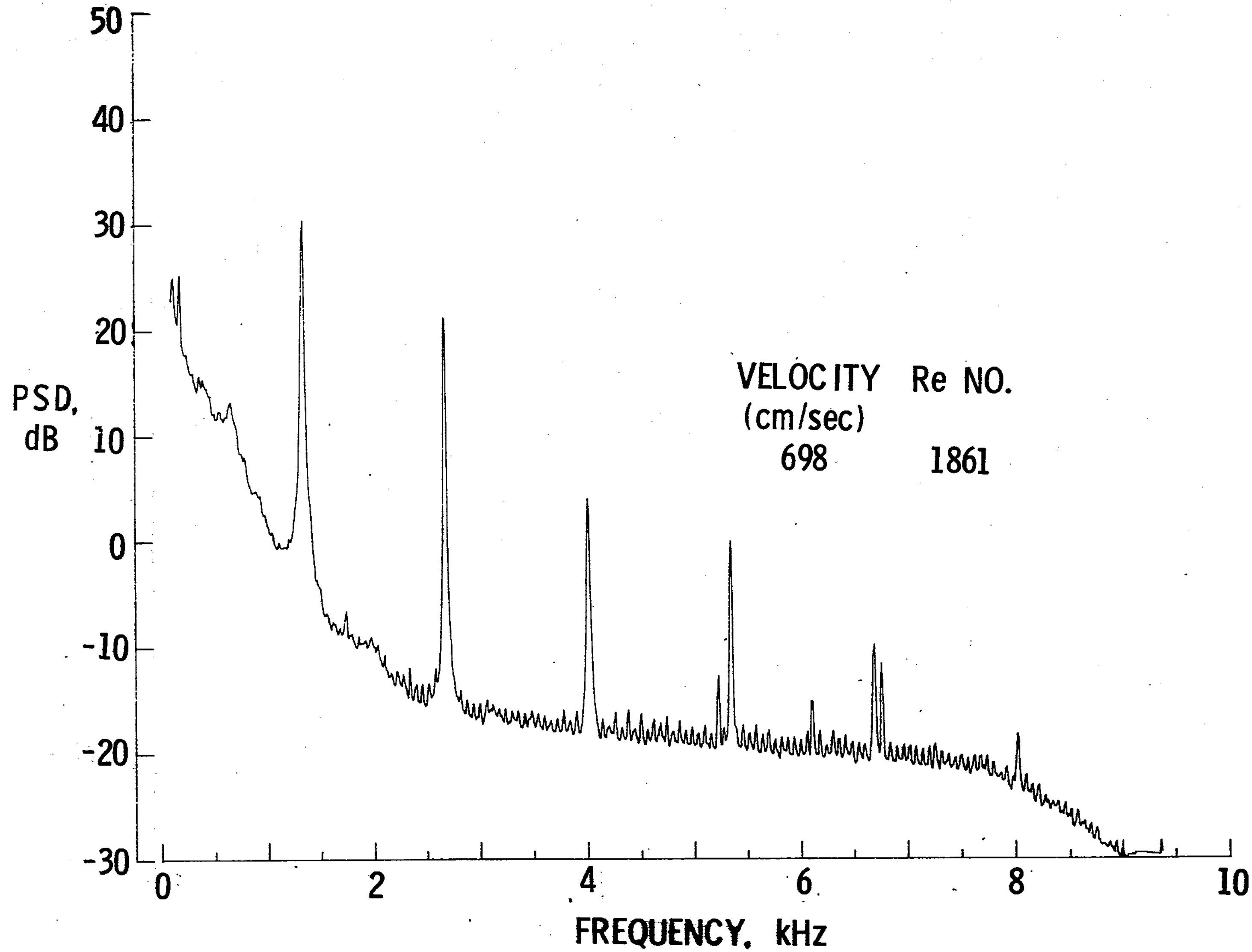

Figure 5: Typical Spectrum in Upper Region

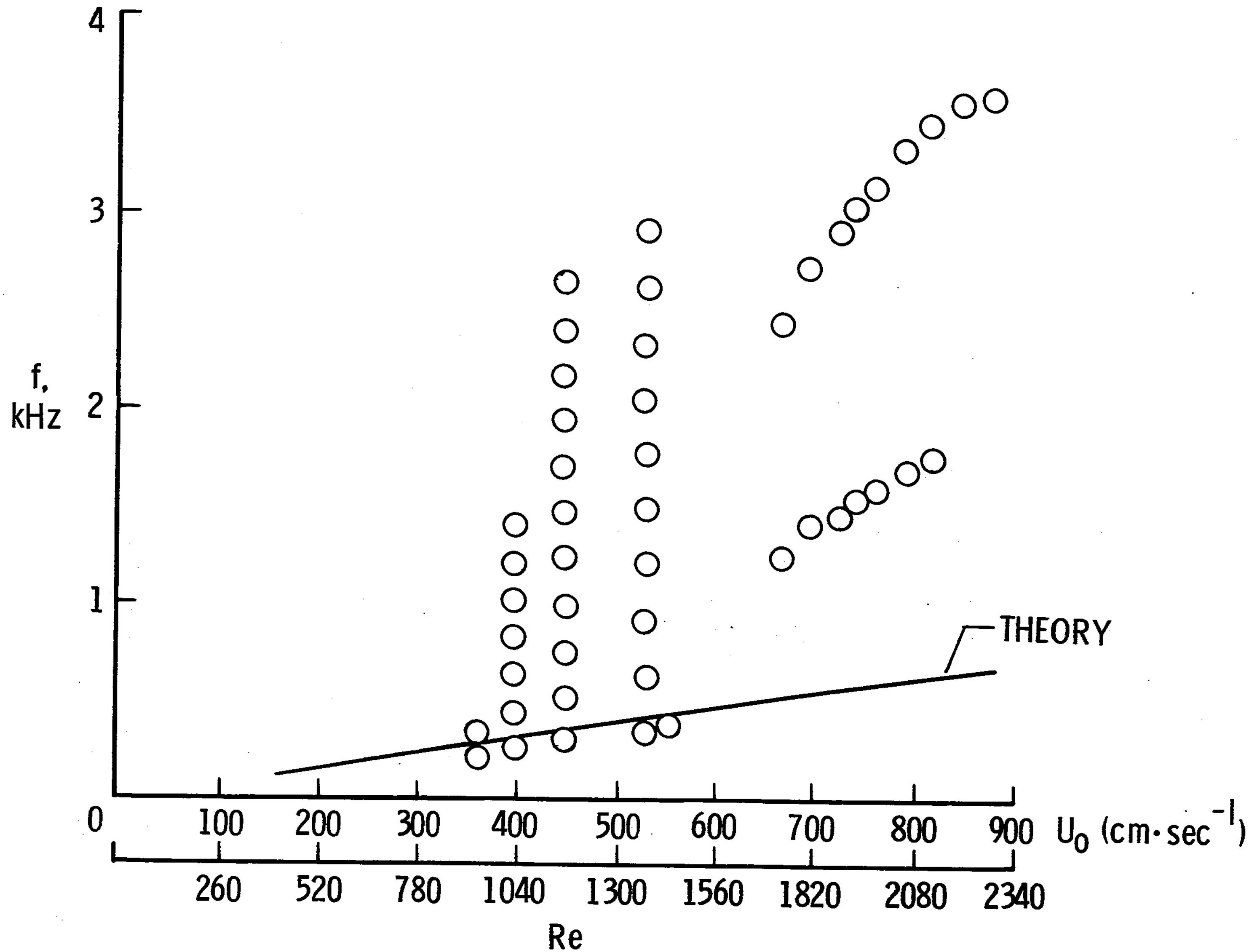

Figure 6: Comparison of Tone Frequencies with Theory

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